High Resolution and Fast Response of Humidity Sensor Based on AlN Cantilever with Two Groups of Segmented Electrodes

Dongsheng Li, Hanyong Dong, Zihao Xie, Qian Zhang, Mengjiao Qu, Yongqing Fu, and Jin Xie, *Member, IEEE*

***Abstract*—Resonant cantilever based on piezoelectric materials is one of the most promising platforms for real-time humidity sensing. In this letter, we propose a humidity sensor based on an AlN piezoelectric microcantilever with a high-order resonant mode and a sensing layer of MoS_2. The top electrode of cantilever is designed into two groups of segmented electrodes in order to achieve a high intensity of the resonance peak of the cantilever resonator operated at a high-order mode. Compared with the humidity sensor based on a standard cantilever with the same dimension, the sensitivity of the newly proposed humidity sensor is increased from 5.99 to 778 Hz/%RH when the humidity is about 80%RH. The resolution is increased from 0.21%RH to 0.025%RH because of the improvement of the ratio of sensitivity to noise, which cannot be achieved simply by increasing the frequency. The sensor shows a low hysteresis (5.8%) in a wide humidity sensing range from 10%RH to 90%RH. Moreover, the proposed humidity sensor has good short-term repeatability, fast response (0.6 s) and recovery (8 s) to humidity changes, indicating its great potential for fast-response detection.**

***Index Terms*—AlN piezoelectric cantilever, high resolution, humidity sensor, MoS_2.**

I. Introduction

HUMIDITY sensor with high sensitivity and resolution, fast response, and wide-range sensing capability is promising for many applications such as agriculture/planting, food storage, and medical diagnosis [1]-[3]. Humidity sensors based on various working principles such as resistance, capacitance, electrochemical sensor, field effect transistor (FET), optical sensor, and mechanical acoustic wave, have been studied for decades [4]-[6]. A piezoelectric resonant cantilever is one of the most promising platforms for real-time humidity sensing owing to its high sensitivity, quick response, easy interfacing with digital signal processing, and ability of self-sensing and self-exciting [7], [8].

Humidity is usually monitored through detecting the shift of resonant frequency of piezoelectric resonant sensors [9]. The sensitivity of these sensors can be improved by using resonators with a higher resonant frequency [10]. High-order modes are often used to increase the resonant frequency of the piezoelectric cantilever [11]. However, these high-order modes of the cantilever resonator often show low intensities of resonance peaks, which will cause low signal to noise ratio, thus not suitable for humidity sensing [12].

Properties of the sensing material greatly affect the responses of the humidity sensor and different humidity-sensing materials have been proposed, such as ceramics, metal oxides, polymers, and nanomaterials [5]. Two-dimensional (2D) materials are ones of the most promising materials for humidity sensing applications, because of their large surface areas, excellent mechanical properties, and capabilities of precise detection at room temperature [13], [14]. Recently, humidity sensors based on molybdenum disulfide (MoS_2) have shown good performance [15]. MoS_2-based humidity sensors were reported to have high sensitivity, fast response and recovery [16].

In this work, an AlN/silicon cantilever resonator was fabricated. In order to achieve high intensity of the resonance peak of the cantilever resonator operated at a high-order mode, the top electrode of the piezoelectric cantilever was divided into two groups of segmented electrodes for better electromechanical transduction. Then MoS_2 thin film was deposited on the surface of the cantilever to form a humidity sensor, which was exposed to a range of humidity conditions. The sensitivity, frequency stability, and resolution of the proposed humidity sensor were investigated and compared with those based on a standard AlN cantilever resonator. We also investigated the hysteresis, short term repeatability, response and recovery time of this humidity sensor.

II. Design and Fabrication

The proposed humidity sensor consists of a piezoelectric cantilever based on AlN and a sensing layer of MoS_2, as shown

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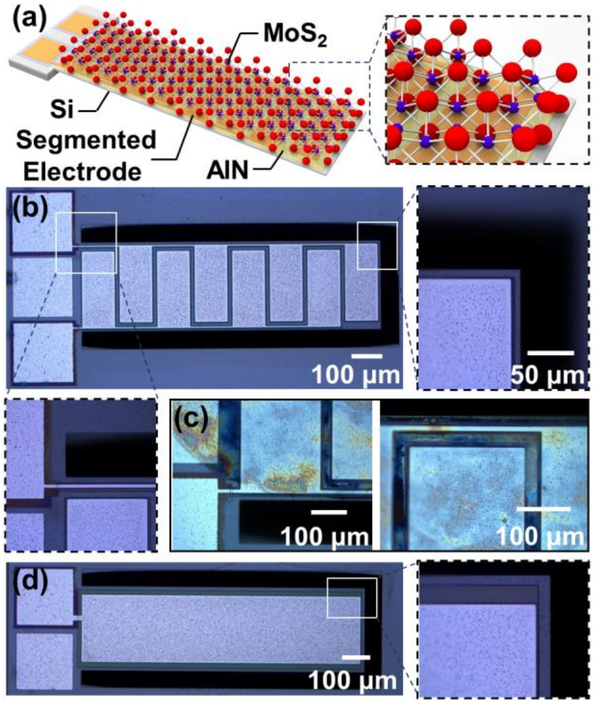

Fig. 1. (a) Schematic of the proposed humidity sensor. Photograph of the AlN cantilever with two groups of segmented electrodes before (b) and after (c) coating with MoS_2. (d) Photograph of the standard AlN cantilever.

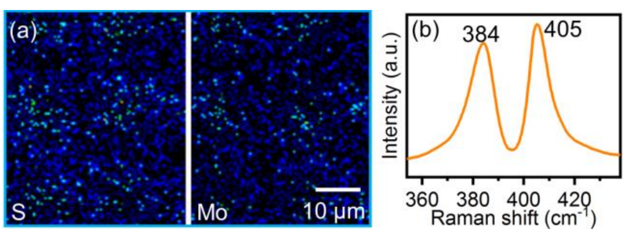

Fig. 2. Elemental mapping images (a) and Raman spectrum (b) of MoS_2.

in Fig. 1a. The area of the cantilever is 300×1000 μm^2. The top electrode is divided into two groups of segmented electrodes (Fig. 1b), in which one group is used as the activating electrode and the other group is used as the receiver for signals. The AlN piezoelectric cantilever was made of bi-layers of 10 μm-thick Si and 0.5 μm-thick AlN. Bimetallic layer of 1 μm aluminum and 20 nm chrome was deposited and patterned on the surface of AlN layer by evaporation and lift-off process to form the top electrodes. The cantilever was released from backside by etching silicon substrate through a standard deep reactive ion etching process [12]. The fabricated cantilevers are shown in Figs. 1b and 1d.

Then the dispersed (0.4 μL) MoS_2 in deionized water with a concentration of 0.1 mg/ml was dropped on the cantilever and dried in a vacuum chamber, thus forming a sensing layer, as shown in Fig. 1c. The thickness of the MoS_2 film is about 150 nm. MoS_2 dispersion is purchased from "Nanjing/Jiangsu XFNANO Materials Tech Co., Ltd". Fig. 2a shows the elemental maps of the MoS_2 film, revealing uniform distributions of Mo and S. Raman spectrum of the MoS_2 film shows two main peaks: E_{2g} peak (roughly at 384 cm^{-1}) and A_{1g} peak (roughly at 405 cm^{-1}), as shown in Fig. 2b.

The humidity-sensing test was carried out by a custom-made humidity sensing system, which has been reported in details in our previous work [17]. The temperature was kept at 22.5 ± 0.5°C during the humidity test.

III. Results and Discussion

Fig. 3a shows the experimentally obtained T/R transmission curves with a frequency range from 10 kHz to 500 kHz of the conventional piezoelectric cantilever which is shown in Fig. 1d. There is no obvious resonance peak when the frequency exceeds 500 kHz due to the low intensity of the resonance peak of the piezoelectric cantilever. Fig. 3b shows the obtained T/R transmission curve of the newly proposed piezoelectric cantilever within the frequency range from 2.78 MHz to 2.83 MHz. There are remarkable resonance peaks in the transmission curve of the proposed cantilever. The insets in Figs. 3a and 3b present the corresponding vibration modes from finite element analysis. The intensity of the resonant peak for the cantilever operated at around 2.8 MHz is intensively improved by applying two groups of segmented electrodes. Fig. 3c shows the measured transmission curve of the proposed cantilever after coated with MoS_2 film. The resonant frequency is slightly reduced after MoS_2 coating.

For the conventional piezoelectric cantilevers excited with one single top electrode, the piezoelectric stress matches the fundamental vibration mode efficiently, and the piezoelectric stress always does positive work on the cantilever at this fundamental resonant frequency. Nevertheless, when the cantilever works at a higher mode, the piezoelectric stress no longer matches with the vibration mode [18]. A part of piezoelectric stress will have negative effect on vibration of the cantilever, which causes inefficient electromechanical transduction and thus a low intensity of the resonance peak of the cantilever [17]. By dividing the top electrodes into two groups of segmented electrodes, the piezoelectric stress generated by electrodes could match the high-order vibration mode, and therefore a high intensity of the resonance peak can be achieved.

Fig. 4a shows resonant frequency shifts of the conventional cantilever-based humidity sensor operated at different modes when the humidity level is changed from 10%RH to 90%RH with an interval of 10%RH. The resonance frequency of the piezoelectric cantilever can be calculated by [19],

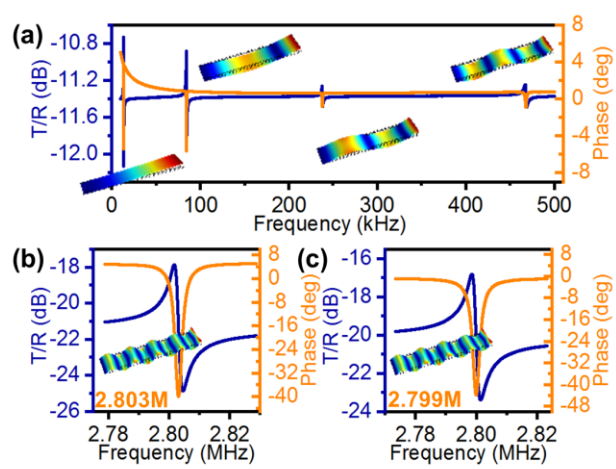

Fig. 3. (a) T/R transmission curve of the normal piezoelectric cantilever. Transmission curve of the proposed AlN cantilever before (b) and after (c) coating.

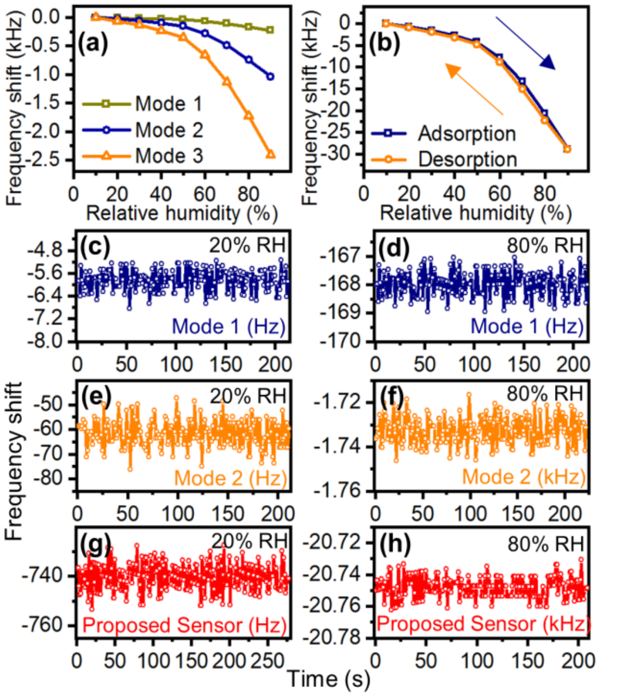

Fig. 4. Frequency responses of the normal cantilever-based humidity sensor working at different modes (a) and the newly proposed humidity sensor (b) when relative humidity changes from 10%RH to 90%RH. (c-h) Fluctuations of the resonant frequencies of the sensors at various conditions.

$$f_n = \left(v_n^2/2\pi L^2\right)\sqrt{D_p/m} \tag{1}$$

where D_p, L, m, and v_n are the bending modulus per unit width, the length, the mass per unit area, and dimensionless eigenvalue of the cantilever, respectively. After the absorption of water molecules on the surface and in the interlayer of the MoS_2 film [20], the mass (m) increases, causing the frequency shift of the humidity sensor.

The frequency shift is not linearly related to humidity change and the sensitivity of the sensor is quite high when the humidity level is relatively high. We take the average sensitivities in the ranges of from 10%RH to 30%RH and 70%RH to 90%RH as those at 20% RH and 80%RH, respectively, considering the nonlinearity of the frequency shift. The sensitivities of the sensor based on the first three modes of the standard cantilever are 5.99, 27.4, 63.7 Hz/%RH, respectively, when the humidity is about 80%RH. Frequency shifts of the newly proposed humidity sensor with the changes of humidity are shown in Fig. 4b. The sensitivity is 778 Hz/RH% when the humidity is about 80%RH, which is much higher than that of the standard sensor. The sensitivity of the newly proposed humidity sensor is improved with the increase of the frequency of the cantilever resonator [19], [21].

The resolution of the humidity sensor, i.e., the minimum humidity change that can be distinguished, is calculated based on the signal-to-noise ratio (S/N > 3), using the following equation [22]:

$$R = 3N / S \tag{2}$$

where R, N, S are resolution, standard deviation of resonant frequency, and sensitivity of the sensor. The fluctuations of the resonant frequencies of the sensors at various conditions are shown in Figs. 4c-h. The resolutions of the conventional sensor based on its first mode are 1.67%RH and 0.21%RH at 20%RH and 80%RH, respectively. The resolutions of the conventional sensor based on its third mode are 2.44%RH and 0.29%RH at 20%RH and 80%RH, respectively. The resolution of the sensor cannot be improved simply by increasing the frequency. Whereas the resolutions of our newly proposed sensor are improved to 0.3%RH and 0.025%RH at 20%RH and 80%RH, respectively. The improvement of resolution is mainly attributed to the suppression of noise level because of the improved intensity of the resonance peak. The proposed sensor also shows a very low hysteresis (5.8%) in a wide humidity range, as shown in Fig. 4b.

The frequency shifts of the proposed humidity sensor were further recorded with a time interval of 0.2 s when the humidity was changes between 10%RH and 80%RH for five cycles. An excellent repeatability is observed over these five cycles of tests, as shown in Fig. 5a. The response time is defined as the time period from resonant frequency starts to change until the frequency shift reaches 90% of its final value. Fig. 5b shows that the proposed sensor has both fast response (0.6 s) and recovery (8 s) to humidity change, which demonstrates its great potential for high-speed humidity detections.

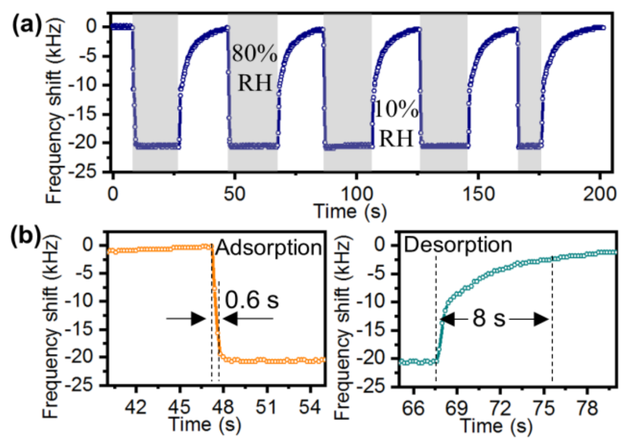

Fig. 5. (a) Dynamic response and (b) detail response and recovery process of the humidity sensor.

IV. Conclusion

We propose a humidity sensor based on an AlN piezoelectric cantilever operated at a high-order mode and a sensing layer of MoS_2. The top electrode of the cantilever is divided into two groups of segmented electrodes in order to obtain a high intensity of the resonance peak of the cantilever resonator operated at a high-order mode. The sensitivity of the proposed humidity sensor is up to 778 Hz/%RH, and the resolution is up to 0.025%RH because of the improvement of the ratio of sensitivity to noise, when the humidity is ~80%RH. Moreover, the proposed sensor has low hysteresis (5.8%), good short-term repeatability, fast response (0.6 s) and recovery (8 s) to humidity change.

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